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# Behaviour of Humans and Behaviour of Models in Dynamic Space

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# BEHAVIOUR OF HUMANS AND BEHAVIOUR OF MODELS IN DYNAMIC SPACE

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**Abstract**

This paper addresses new trends in quantitative geography research. Modern social science research – including economic and social geography – has in the past decades shown an increasing interest in micro-oriented behaviour of actors. This is inter alia clearly reflected in spatial interaction models (SIMs), where discrete choice approaches have assumed a powerful position. This paper aims to provide in particular a concise review of micro-based research, with the aim to review the potential – but also the caveats – of micro models to map out human behaviour. In particular, attention will be devoted to interactive learning principles that shape individual decisions. Lessons from cognitive sciences will be put forward and illustrated, amongst others on the basis of computational neural networks or spatial econometric approaches. The methodology of deductive reasoning under conditions of large data bases in studying human mobility will be questioned as well. In this context more extensive attention is given to *ceteris paribus* conditions and evolutionary thinking.

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> *"As far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality".*
>
> (Albert Einstein)

## 1. Prefatory Remarks

One of the most revolutionary developments in our age has been the rapid introduction of *miniaturisation* in all fields of industrial technology, e.g. in materials use, medical science, information and communication technology (ICT), small particles physics, or chemistry. The search for small items or particles in the natural sciences was encouraged by a seminal article of Richard Feynman (1960), who caused a radical transformation in fundamental research in physics and chemistry through his challenging article *"There is plenty of room at the bottom"*. His scientific work laid the foundation for the emergence and rising popularity of nanotechnology, essentially characterized by the motto *'small is beautiful'*. Not only is it possible nowadays to store an entire *'lab on a chip'*, but also to store more information on the *'top of a pin'* than on a mainframe computer a few decades ago.

These new developments are possible thanks to interconnected technologies and interoperable information systems (see also Haining et al. 2010). Similar trends can be observed in research in behavioural sciences, such as experimental psychology, micro-economics, criminology, transportation science and human geography. An example is spatial interaction modelling based on discrete choice analysis, such as logit or probit models. Modern ICT developments and advanced statistical storage and data mining techniques have led to a drastic re-orientation in applied research in the behavioural sciences, along two lines. First, we observe a clear emphasis on *micro* (individual) data (e.g. panel and longitudinal studies, individual survey questionnaires, interconnected data bases). And next, we see the emergence of *extensive data bases* (for instance, permanent observation and monitoring of individual traffic behaviour), which far exceed the limited empirical information on human behaviour in the past. This trend towards a wealth of individual multi-actor behavioural data calls for a more systemic approach in applied research, e.g. complexity analysis, agent-based modelling, evolutionary behavioural geography and so forth (see also Bavaud and Mager 2009).

From a methodological perspective, the unprecedented volumes of data in our age question the relevance of a nomothetic or deductive approach in behavioural research. The traditional research tradition starts from a series of propositions and testable hypotheses, to be validated by (often limited) empirical data (through the use of econometric models or appropriate statistical techniques). But in modern behavioural research, the volumes of data are sometimes extremely rich and extensive, so that a consistent testing of theoretical concepts many become so cumbersome, that Hempel's *'bridge principle'* can hardly be met. A reverse methodological departure is nowadays becoming more popular and appropriate, namely *'letting the data speak for themselves'* (data-instigated theory). Through statistical identification techniques it is then possible to trace hidden structures in large data sets, which may then form a basis for new theory development, based on cognitive research approaches ('computational social sciences'; see Lazer et al. 2009). This implies inter alia more emphasis on heuristic or *'data-rich'* and *'theory-free'* statistical techniques such as computational neural networks, genetic algorithms or self-organizing mapping procedures.

In the present paper we will address new research challenges in the area of spatial analysis and modelling. After an illustration of the use of micro GSM data in a space-time micro context, we will offer some conceptual observations on new trends in quantitative research on nonlinear dynamic spaces. Next, we will address a cumbersome concept in spatial research, viz. the *ceteris paribus* condition in relation to spatial equilibria, and review its relevance in data-instigated research. We will then move on and devote some attention to spatial complexity analysis, followed by a review of recent applications. In this context, spatial networks offer a great research field for investigating the structural patterns in complex and dynamic systems. In this vein we also address evolutionary thinking in geography, while, finally, we draw some research conclusions.

## 2. Illustration: Micro-electronic Footprint Data in Space-Time Geography

Geography has increasingly lost the traces of a descriptive discipline on man-environment relationships. On the contrary, modern geography has increasingly turned into a data-handling scientific activity over the past decades. Transport geography offers a clear illustration of this trend. The methodology of data collection – and subsequent statistical analysis in spatial interaction modelling – has exhibited drastic changes over the years. Many flow models used in the transportation field (e.g. for commuting, shopping, recreation, freight transport) have traditionally used origin-destination (OD) data, either at an individual or at an aggregate level. Most of these models were based on gravity-type of approaches, which later on were often translated into spatial interaction models (SIMs). Well-known examples are entropy models and activity-based spatial models. All these approaches needed extensive data, obtained from either observed flows (e.g. manual counting, loop detection, cameras) or from (self-)reporting methods (e.g. mobility diaries, electronic devices, survey methods or telephone interviews). The increase in large-scale data bases on the spatial behaviour of people (see Hägerstrand 1970) laid the foundation for the operational nature of modern geography.

The history of quantitative data analysis in geography spans already several decades. The need for a more appropriate behavioural underpinning of spatial interaction models led in the 1980s to the emergence and popularity of discrete utility (or choice) models, in particular multinomial logit and probit models, later on followed by conjoint analysis modelling. Such individually-based models were proven to be consistent with aggregate-oriented spatial interaction models and got widely accepted in the transport research community. They also turned out to be well suitable for actor-based policy simulation experiments, for instance, in the context of micro-simulation models and agent-based models. In this vein, modern geography exhibits increasingly the methodology of the natural sciences based on advanced statistical analysis and testable models (see, for a review, Pagliara and Timmermans 2009).

All such models were widely used for prediction purposes, evaluation experiments and policy analyses in the planning and transportation science field, for example, to trace the system-wide effects of road pricing on the behaviour of car drivers. With the advent and introduction of ICT, the computing capacity in quantitative research showed a dramatic increase, so that also spatial dynamics could be captured in a statistically more satisfactory way. Complexity theory has in recent years offered a remarkable contribution to a better understanding of the sensitivity of spatial systems' evolution to endogenous non-linear space-time behaviour. Space-time dynamics (e.g. in the cellular automata domain) became an important ingredient of advanced transportation research and spatial analysis, and prompted a new departure, viz. the use of data mining methods for large data sets (see also Batty 2005). The current use of computational neural networks and genetic algorithms demonstrates convincingly the great potential of more sophisticated data collection techniques. The real essence of space as highlighted in Tobler's (1970) law ("*all things in space are related to each other, but nearby things are more related than distant things*") was taken up in a new strand of literature addressing spatial – and spatio-temporal – autocorrelation, either as testing devises or as design mechanisms for spatial (dynamic) models (see also Tobler 2004). Cellular automata, spatial filtering techniques and self-organized mapping procedures ('Kohonen maps') for spatial interaction analysis were a logical follow-up and complement to the above mentioned trends (see e.g. Arribas et al. 2010, Codd 1968, Couclelis 1997, Kohonen 2000, Kulkarni et al. 2002 and Patuelli et al. 2010).

In recent years, we have witnessed an increasing popularity of location-based services (LBS) and data using various kinds of electronic identification systems, so that at an individual level (a traveller, a container, a truck, or a taxi) the geographic position of a unit can be traced with great precision. Many applications are available for purchase and free to cell phone and other wireless device users. For example, Japanese parents are using location-based tracking devices to monitor the spatial movement of their kids. This new approach will certainly prompt many new applications in space-time geography.

An interesting source of individually-based information on the space-time position and behaviour of persons is in principle available from mobile (or cell) phone data, derived from the GSM network. The penetration rate of mobile phones is rapidly reaching a full saturation level in most OECD countries, so that a system-wide coverage does in principle exit, almost in continuous space-time format. Such data – as very accurate representations of the individual space-time location – are in principle available with telephone operators. If such data – in anonymous form – could be made available to the research community, an unprecedented source of information on the space-time geography of individuals could be used in applied research (see for an overview Steenbruggen et al. 2010).

It is noteworthy that this idea of a continuous space-time map at an individual scale was already put forward by the late Swedish geographer Torsten Hägerstrand in 1967. He introduced the 'space-time cylinder' and its related time-space model (see also Figure 1) to offer a description of both individual space-time patterns and the resulting spatial interactions if many individuals were 'en route' at the same time and place, a situation caused by the universal limited supply of daily time resources. His work was regarded as a new perspective in social-behavioural geography, as it highlighted so clearly the essence of interaction and congestion phenomena in space (see Pred 1977). Three constraints appear to act as constraints on the daily mobility pattern of individuals, viz. capability constraints, coupling constraints and authority constraints. It also laid the foundation for activity-based transport geography, but, unfortunately, lack of data and the technology available to implement the framework precluded often a full operational application of his path-breaking ideas. Now with the potential availability of large-scale continuous space-time information bases on spatial movements of individuals, a really interesting novel approach might be developed, which may have great implications for spatial modelling. Two such approaches can be found in the literature. The first incorporates elements of cognition by considering individuals' preferences via the theory of affordances proposed by Gibson (1979) (Raubal et al 2004). Cognitive constraints, e.g., choice behaviour, were not given explicit attention in the original time-geography framework. These constraints can help personalize LBS, allowing for the possibility to collect more detailed information about the choices individuals make, their likes and dislikes. The second adjusts the space-time prism concept to support interactions and activities between the physical and virtual spaces (Yu and Shaw 2008). This approach would help model and understand how in the age of mobile computing, where a variety of activities and services can be carried out on the go, individuals are allocating their space and time resources.

In the literature, we see already the first interesting applications of GSM data, e.g. in the study of intensity of social networks (Eagle et al. 2009), the spatial distribution and concentration of tourists (Ahas et al. 2006), traffic speed and journey time (Bar-Gera 2007), individual mobility patterns in cities (Gonzales et al. 2008) or of urban structure patterns (Reades et al. 2009). Interesting applications can also be found in the use of private or public spaces by individuals (see, e.g., Calabrese et al. 2001), the concentration of people in a city (see, e.g., Reades et al. 2009), the activity spaces of commuters (see Ahas et al. 2006), non-recurrent mass events such as a popfestival (see, e.g., Reades et al. 2007), the entry of tourists in a certain area of attraction (see e.g., Ahas et al. 2007, Ahas et al. 2008), or the estimation of spatial friendship network structures (see Eagle et al. 2009). Especially in the transportation sector, the potential applications are vast, and consequently, the use of cell phone data has shown a rapid increase in urban transport applications. These data offer a rich source of information on continuous space-time geography in urban areas. They can be used for daily traffic management, but also for incidence management, for instance, in case of big fatalities, terrorist attacks, or mass social events such as festivals or demonstrations.

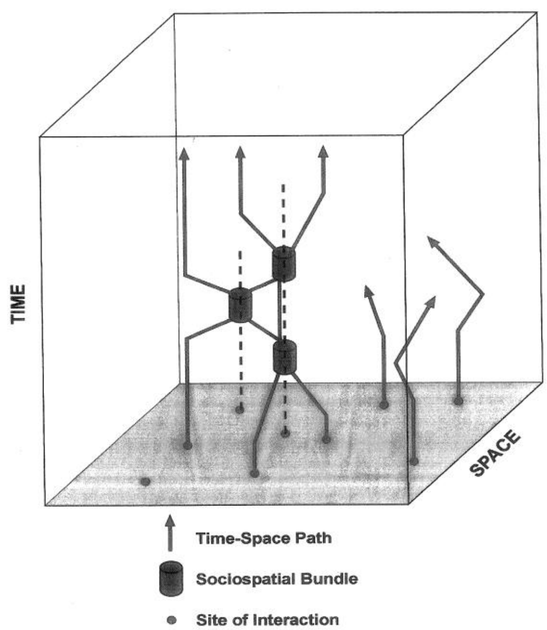


**Figure 1.** Hägerstrand's Time-Space Model
**Source:** Warf (2006)

It should be noted that the use of LBS data (either GPS or GSM information) has also met scepticism and even criticism, as in this case it may be possible to track humans in all their space-time movements. Some authors talk even about *'geoslavery'*[1] as a new form of big-brother

[1] Geoslavery is in the 'Encyclopedia of Human Geography' (p. 186) defined as follows: "*Geoslavery is a radically new form of human bondage characterized by location control via electronic tracking devices. Formally, it is defined as a practice in which one entity (the master) coercively or surreptitiously monitors and exerts control over the physical location of another individual (the slave). Inherent in this concept is the potential for a master to*

control on location behaviour (see, e.g., Dobson and Fisher, 2003; Reades 2010) and highlight important privacy issues (Sui 2004, Jiang and Yao 2006). Notwithstanding such socio-ethical issues, GIS technology offers an important vehicle for the use of such geo-based devices for mobility planning and management. The Open GIS Consortium (OGC) (http://www.opengis.org) through the OpenGIS Location Service (OPENLS) initiative has defined standards to facilitate the interaction with LBS. ESRI the largest GIS company world-wide (Shiode et al. 2002) as part of its efforts to stay in the forefront of GIS technology has offered its services as part of the Amazon Cloud (ESRI 2010) (for a discussion on cloud computing for mobile users see Kumar and Lu 2010). This will provide organization the ability to run GIS services in the cloud without having to purchase the software. This in turn will offer LBS additional functionalities previously unavailable that can manipulate and analyze the spatial data given even more importance to the development of new approaches in the field of time-geography.

Modern GIS technology in combination with location based services (LBS) – in the context of either GPS or GSM systems – is indeed able to design real-time tracking and tracing systems for goods and people. Especially the integration of spatial integration and individual information from various sources has raised public concern on personal surveillance and information privacy. As mentioned above, in principle an integrated space-time information system may pave the road towards permanent location control, coined geoslavery (see Dobson and Fisher 2003, Goss 1995). Clearly, the advantages of remote-control tracking and tracing systems are numerous, for instance, in route navigation systems, LBS in the trucking sector, wristbands for tracking the movements of schoolchildren, incident identification among mountaineers, spatial positioning of temporarily released prisoners, etc. However, there are evidently also shadow sides to be faced by public authorities and commercial vendors or marketers aiming at exploiting the potential of such electronic information systems, in particular as an 'information master' may structurally control time, location, speed and direction for every movement of any individual. It is clear that specific regulations on the use of and access to such electronic tracking and controlling systems are needed to prevent any abuse and violation of privacy protection.

The previous observations offer a clear demonstration of the radical changes in modern geographical research, where large micro data bases offer an unprecedented scope for detailed spatial analysis of human behaviour. This new opportunity calls also for a more critical reflection on the research methodology of geography. The latter issues will be touched upon in the next section, which is more explicitly devoted to the spatial footprints of GSM networks.

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*routinely control time, location, speed, and direction for each and every movement of the slave or, indeed, of many slaves simultaneously. Enhanced surveillance and control may be attained through complementary monitoring of functional indicators such as body temperature, heart rate, and perspiration*".

## 3. Organizing Principles for the Space-Economy: A Conceptual Overview

The research domain of modern geography is vast and is increasingly interacting with other disciplines, such as economics, law, planning, political science, sociology and architecture. This trend has caused an important interdisciplinary cross-fertilization and has also prompted a rapid introduction of advanced research tools such as dynamic systems models, computable spatial economic equilibrium models (for instance, in the new economy geography), spatial interaction analysis, discrete choice models, spatial network analysis, spatial innovation and diffusion analysis, migration studies and so forth. Modern data mining techniques are important vehicles in this context.

Another set of important statistical tools that have been developed in the past decades is offered by spatial econometrics which has gained much popularity in recent quantitative regional and urban research. Spatial econometrics has already a long history. It started as a simple statistical test to detect spatial autocorrelation (or spatio-temporal autocorrelation) in a multi-regional data set by using Moran statistics. Later on, it was realized that the use of spatially correlated data in multiregional models might lead to biased estimators (see Anselin and Rey 2010). Two pathways were essentially developed to cope with autocorrelation in spatial models with interaction effects, viz. the spatial lag model and the spatial error model. The first class includes a spatially lagged dependent variable, while the second class contains a spatial auto-regressive error term expression. Spatial econometrics has gained a great deal of popularity in modern quantitative geographical research and has become a standard tool in this field. Over the years, much progress has been made by combining a spatially lagged dependent variable and a spatially autocorrelated error term in one model, while more recently also combined spatially lagged dependent and explanatory variables have been developed (the 'spatial Durbin model') (LeSage and Pace 2009; Elhorst 2010).

A major limitation in current spatial econometrics research – and a great future research challenge – is the fact that the determination of the spatial weight matrix is still fraught with many uncertainties. Essentially, the way a spatial weight matrix $W$ is normally estimated (e.g., via the reverse distance between adjacent regions, the length of the common border between contiguous areas) is rather naive and does not incorporate any cognitive information on the interaction intensity among regions, such as socio-cultural cohesion, behavioural commonalities, interlinked institutional regimes. There is no doubt much scope for further sophisticated research by endogenizing the specification of the $W$ matrix. In this context, adjusted techniques – based on e.g. instrumental variables methods – may have to be employed. Similar observations can be made on space-time autocorrelation, where the combined lag structure – over space and time – needs more careful attention.

It should be noted that one issue has received less attention in quantitative applied research, namely the management of geographical space (e.g. sustainable land use planning), which has assumed a far less prominent place in spatial statistics and modelling, although the current popularity of complex and self-organizing systems is a promising new departure (see Portugali 2006). Planning of space (e.g. land use, infrastructure) has in recent years been positioned in an evolutionary world, which is less dictated by top-down control, but much more by micro behaviour from a bottom-up perspective in which learning and interaction play a crucial role. The development of spatial mega data systems ties in with these new trends in planning, which has over the past years increasingly moved into coordination of spatial developments rather than command and control of spatial developments (see Portugali 2000).

Clearly, the existence of spatial externalities (e.g. density effects, environmental decay) will always prompt a call for intervention, but the nature of this intervention shows in recent years a tendency towards a conviction rather that a coercion mode. In the recent literature we observe an increasing popularity of self-organizing principles for dynamic interactive spatial systems. This runs parallel to the rising acceptance and use of spatial complexity concepts (see also Section 5), which are essentially based on nonlinear, dynamic interaction effects among agents in space. Such effects are usually characterized by a multidisciplinary and multi-actor constellation, with various feedback and learning effects. Consequently, spatial governance systems have been re-modelled into game-like negotiation strategies, in which public actors have become an endogenous part of a broader policy system.

Despite the changing nature of planning principles and practice, there is still the need for efficient and effective ordering principles. In his seminal article on the *'Architecture of Complexity'*, Simon (1962) makes an original attempt to formulate some general organizing principles for systems subject to systemic complexity. His governance rules are essentially based on three anchor points: the existence of the bounded rationally paradigm, the adoption of learning principles, and the use of decomposed hierarchical principles favouring management efficiency. This approach is essentially an attempt to reduce complexity to 'simplexity'.

From an analytical perspective (see Reggiani and Nijkamp 2009), a wealth of concepts and models has been developed over the past two decades, in particular: bifurcation, chaos, synergetics, resilience, complex networks, evolutionary behaviour, scale-free networks, criticality, or small-world networks. Many of these models are purely illustrative and pedagogical in nature, but in recent years we have witnessed various interesting applications, for example, in traffic management, ecosystems policy, ethnic conflict management, medical treatment and therapy, financial crisis management, innovation policy and urban evolutionary development.

Such new analytical departures originate from well-known and solid frameworks, such as gravity theory, entropy modelling, neural network analysis, genetic algorithms applications, Thuring principles, power laws, preferential attachment principles etc. It is noteworthy that in their spatial manifestation, many of these principles are directly or indirectly rooted in Tobler's first law (which is essentially a consequence of the gravity principle).

It is important to note that many of the above mentioned modelling types are rather general natural science tools – and not necessarily specific behavioural analysis tools –, so that the question may be raised whether such models are relevant and appropriate research tools in analyzing the space-economy. The use of the methodology of 'social physics' presupposes the fulfilment of two conditions: (i) a formal correspondence between relevant social science and natural science phenomena; (ii) a substantive behavioural interpretation of 'social physics' models, so that behavioural motives can be traced in such models. It is important to mention here that in many cases these two conditions are met (for example, entropy models are essentially generalized cost minimization models), so that then there is hardly a valid counter-argument to find for the use of social physics models in geography.

Clearly, social physics is a translational research approach in which findings from one discipline are incorporated in the research design in another discipline. But this is only a partial strategy to study real-world phenomena from a perspective of multiple disciplines. The challenge of interdisciplinary research boils essentially down to a methodological issue on the demarcation lines and bridges between distinct disciplines. This will be further outlined in the next section.

## 4. *Ceteris Paribus* in the Modern Space-Economy

Social science theory and application has in its long history adopted a consistent, though rather restrictive, methodological approach in dealing with the presence of multiple disciplines by drawing strict border lines and assuming developments in a different disciplinary domain as given. For example, location analysis in economic geography took for granted that psychological perception and preference formations were handled by psychologists, while the results of individual preferences were assumed to be given for the economic geographer, without asking whether there might be feedback effects through which geographical space might impact on preference formation or spatial attitudes. The simplifying and stylized assumption in such a reductionist approach increased the consistency but not necessarily the realism in regional and urban research (see also Nijkamp 2007).

Such a reductionist assumption originates essentially from a *ceteris paribus* condition which has been introduced in social science research to handle in a consistent way system-internal (endogenous) and system-external (exogenous) factors. The focus on a few selected variables in a research design leads of course to a streamlined approach, although this is not strictly needed from a conceptual or logical perspective (Nijkamp 2007). This approach may in real-world applications even frustrate transferability of scientific findings to other empirical domains. Admittedly, the *ceteris paribus* condition forces the research to concentrate on the main factors to be studied, so that – in a partial sense – strict inferences can be drawn. Interestingly enough, the *ceteris paribus* has already a long history; according to Persky (1990) its earliest use in the current meaning dates back to the year 1311(!), when it was already used in scholastic philosophy. The *ceteris paribus* postulate was introduced as a major analytical tool in economic equilibrium analysis since the seminal work of Marshall (1898), who needed a demarcation of his economic research domain in order to guarantee a partial equilibrium. Even though general equilibrium theory was able to relax the *ceteris paribus* assumptions, the necessity to introduce stylized assumptions was never questioned, even not in spatial equilibrium theory, general systems analysis and computable general equilibrium theory.

With the advent of dynamic and complexity systems, the issue of the demarcation of disciplines and research domains has seen a revival. For example, if we make a distinction between fast and slow dynamics in space (e.g. fluctuating daily traffic flows versus the construction of transport infrastructure), it is questionable which factors have to be regarded as constant in the same model. Clearly, as Kaldor (1985) has argued in his Okun Memorial lecture, it is difficult to imagine economics without equilibrium; the *ceteris paribus* is a postulate that is critical in standard economic equilibrium thinking, Kaldor then continues: " It seems clear that if we are to get out of the present impasse we must begin by constructing a different kind of abstract model, one that recognizes from the beginning that time is a continuing and irreversible process; that it is impossible to assume the constancy of anything over time, such as the supply of labour or capital, the psychological preferences for commodities, the nature and number of commodities, or technical knowledge" (Kaldor, 1985, p. 61).

New methodological departures may perhaps circumnavigate the strict limitations of a *ceteris paribus* approach, such as the analysis of dissipative spatial structures, complexity theory, evolutionary approaches or the use of cognitive (or learning) principles. An interesting challenge is offered by the above mentioned trend towards data-driven research, in which spatial econometrics and spatial filtering approaches may relax the limitations of a strict *ceteris paribus* postulate. These issues prompt certainly a new debate on specification theory in behavioural spatial research.

The *ceteris paribus* condition has been the crucial element in equilibrium theory, as this is the only tool to identify the conditions under which a space-economy is in balance. However, with the increasing availability of large data sets (and with the emergence of advanced data mining techniques) the specification of spatial equilibrium models – with a large share of *ceteris paribus* conditions – is becoming less relevant, as such an extensive data set may contain a multiplicity of *ceteris paribus* variables. Consequently, the specification of spatially autocorrelated models becomes more problematic, so that it seems plausible that exploratory spatial autocorrelation modes will gain more importance in the future.

Next, there is another trend in *ceteris paribus* research, namely controlled experimentation through so-called CP-networks. In this way, micro-information on user preferences can be handled in the context of automated decision making on the basis of *ceteris paribus* interpretations (see, e.g., Boutilier et al. 2004; McGeachie and Doyle 2002).

Finally, *ceteris paribus* plays also a role in counterfactual analysis, which aims to trace alternative developments under 'what if' or 'what if not' conditions. A good example can be found in a recent study on the efficiency of the Victorian British Railway Networks by Casson (2009). Also here, the spatial interaction component plays a critical role.

## 5. Spatial-Economic Complexity

> "*I truly believe that we are at the threshold of understanding complexity.*"
>
> *(…)*
>
> *"The real reason is the data: when it comes to our social and economic systems, we can increasingly monitor what is going on. We can trace where people are, when and with whom they communicate, we can track shopping and travel patterns, and so on. To be sure, these penetrating technologies raise fundamental questions about privacy."*
>
> *(…)*
>
> *"Much of our previous work in complexity was driven by theory, by ideas that were not always well rooted in reality. On the back of network theory a new, quite pragmatic approach to complexity is emerging: one which is driven by data and by measurements, and which leads to theories that are motivated by a deep desire to understand what is really going on. This data-rich era is creating an unprecedented opportunity, and all we need is the right attitude to crack the mysteries of complex systems."*
>
> (Barabasi 2009, p. 26)

Complexity has turned into a fashionable concept in contemporaneous dynamic research. Complexity refers to an organized structure that is driven by multi-actor interactions at various scale levels, where selection and learning play a key role. They lead to non-linear systemic feedback effects that through path dependency and fast and slow nonlinear dynamics create the conditions for unexpected developmental trajectories of a system (Reggiani and Nijkamp 2009). It is not a surprise that complexity research is often linked to resilience, sustainability, Volterra-

Lotka and predator-prey dynamics, symbiosis and self-organization. Complexity forms a contrast with traditional reductionism, as in a complex system the macro behaviour of a system cannot be unambiguously understood from the emergent properties of the constituent elements that may have self-organizing local interactions. This interaction at various scale levels implies that complex systems are closely related to dynamic networks. It goes without saying that complex systems prompt various serious questions on the predictability of such systems, on the relation between emergent properties and micro interactions, on the origin and nature of self-organization and learning, on the stochasticity in complex models, on the simplicity-simplexity-complexity chain, and on the econometrics of such models.

Usually, complex systems have a multiplicity of interacting elements or modules, so that graph theory may be an appropriate analytical tool in the study of complex systems. Mobility, airline connections or Hägerstrand's space-time geography provide illuminating examples of complex networks.

Research on the behaviour of networks started with the introduction of random graphs in which networks nodes were randomly connected by links (see Erdös and Rényi 1959). A drawback of this approach was that such networks displayed a highly regular structure, which forms a contradiction with real-world phenomena where unequal distributions and concentrations are likely to appear.

A new perspective was offered by the introduction of small-world networks by Watts and Strogatz (1998), who designed a simple network on a ring in which each node is only linked to its nearest neighbours. These networks, coined small-world networks, offered a broad spectrum of organized and random patterns.

Almost simultaneously, Barabasi and Albert (1999) provided a new extension, by introducing the principle of preferential attachment, through which an extension of a network by the addition of a node could be analyzed. Preferential attachment means essentially that a new node seeks for connectivity with an existing node that is well-connected to the rest of the network, so that distance friction costs to other nodes are minimal. In this framework, the so-called scale-free networks were introduced. Such networks may have a relevance for hub-and-spoke systems in the airline sector (see Reggiani and Nijkamp 2010) or for social networks (see Boccaletti et al. 2006). The degree distributions can be related to a power law, as this distribution describes a structure with a high connectivity for a few central places (hubs) in the network and a low connectivity for other nodes. The hubs have of course sensitive positions in a scale-free network, at least in case of drastic changes.

Research in geography on complex spatial systems has in recent years shown a rapid rise in scientific interest. Applications include inter alia:

- morphogenesis of cities (Batty 2005; Medda et al. 2009)

- configuration of airline networks (Reggiani and Nijkamp 2010)
- urban evolution (Wilson 2009; Rozenblat and Melançon 2009)
- geography of internet infrastructure (Tranos 2005)
- dynamics in residential locations (Fotheringham et al. 2002)
- complex urban and regional systems (Bertuglia and Vaio 2009; Portugali 2004, 2008)
- urban networks dynamics (Andersson et al. 2006)
- small spatial networks (Gorman and Kulkarni 2004).

In conclusion, complexity theory offers an entirely new reason for quantitative dynamic research in geography. The main challenge for the years ahead will be the operational development of testable models that can stand the scrutiny of the real world.

Next to complexity models, we have in recent years also witnessed the emergence of another, related strand of literature, namely evolutionary thinking in geography. This will briefly be discussed in the next section.

## 6. Evolutionary Thinking in Geography

> "*Darwinism is too important to be left to the biologists"*
>
> (J. Mokyr)

Evolutionary thinking has gradually entered the domain of the social sciences, be it with some hesitation and criticism (see, e.g., Gough et al. 2008). In some disciplines, such as economics (see Nelson and Winter 1982), it has gained a respectable position, but in other disciplines it is still at the beginning of its life cycle. A field where evolutionary thinking has been widely adopted is ecological economics (see Boulding 1981; Georgescu-Roegen 1971; Penn 2003; Van den Bergh 2007, Van den Bergh et al. 2007). Penn offers an interesting evolutionary-oriented explanation of *"why humans are ecologically destructive, overpopulate, overconsume, exhaust common pool resources, discount the future, and respond maladaptively to modern environmental hazards"* (Penn 2003, p. 1). In his view, instigated by evolutionary thinking, human-based environmental decay originates from a poor adaptability of the human species to its environment. It is clear that the rational decision-making paradigm based on selfish agents and oriented towards short-term utility is not compatible with long-term sustainable development. In a recent article, Van den Bergh (2007) offers an insightful overview of the distinct features of evolutionary, ecological, and mainstream environmental and resources economics (see Table 1).

Evolutionary thinking questions also the relevance of GDP per capita as a relevant and reliable growth indicator (or indicator of social welfare). An alternative way of conceiving of welfare growth is to introduce the notion of evolutionary growth, which may comprise concepts like: increasing diversity, increasing complexity, extended division of labour, new ways of transmitting information, population growth, or adaptation (see Van den Bergh 2007).

**Table 1.** Differences in emphasis between evolutionary, ecological and mainstream environmental and resource economics

| **Evolutionary economics** | **Ecological economics** | **Environmental economics** |
|---|---|---|
| Evolutionary potential | Optimal scale | Optimal allocation |
| Agent, technique, and product diversity | Biodiversity | Representative agents |
| Innovation-recombination/mutation | Divergent views on innovation | Optimal R&D |
| Fitness | Equity (intra/intergenerational) | Efficiency, cost-effectiveness |
| Evolutionary stability | Resilience | Sustainable macro growth |
| Adaptive limits | Limits to growth | Growth of limits |
| Path-dependence | Ecological irreversibility | Economic irreversibility |
| Varying time scales | Medium/long run | Short/medium run |
| Population/distribution indicators | Physical and biological indicators | Monetary indicators |
| Bounded rationality and selection | Myopic behaviour | Rational behaviour |
| Functional morality (fitness) | Environmental ethics | Utilitarianism |
| Adaptive individuals and systems | Causal processes | Equilibrium, comparative statics/dynamics |

**Source:** adapted from van den Bergh (2004).

It should be noted that many evolutionary contributions to social science are not based on hard-core Darwinism but rather on interpretative or symbolic similarities to Darwinism using metaphors from evolution theory. For instance, in geography, scholars talk more about evolutionary thinking in geography than about evolutionary geography. In the same vein, evolutionary modelling is often an adjustment of standard dynamic modelling with a few symbolic components instigated by evolutionary thinking. An interesting contribution to the debate on evolutionary modelling can be found in a recent study by Safarzynska (2010), who made a successful attempt to design a series of cornerstones for evolutionary models in ecological economics. She mentions the following ingredients as a necessary condition:

- diversity;
- innovation and selection;
- bounded rationality;
- diffusion;
- path dependency and lock-in;
- co-evolution;

- multilevel and group selection;
- indigenous growth mechanisms.

In her study she shows that advanced evolutionary modelling techniques may mean a particularly important and applied breakthrough in the following research domains:

- evolutionary game theory and selection dynamics;
- evolutionary computation;
- multi-agent modelling.

It is noteworthy that there appears to be a striking parallel between evolutionary modelling and artificial intelligence, in particular in the following fields:

- computational neural networks (see, e.g., Fischer et al. 2010);
- self-organized criticality (see, e.g., Reggiani and Nijkamp 2009);
- adaptive learning models (see, e.g., Bertuglia and Vaio 2009);
- self-organizing mapping procedures (see, e.g., Kohonen 2000).

Applications of evolutionary approaches to geography are still rare, as it has taken some time before the discipline has adopted this new paradigm. One of the reasons is that at the same time, the new economic geography has come into being (see Krugman 1991), which argued that the distribution of economic activity is the result of long-lasting agglomeration forces and interregional or international trade in an open economic system. The new economic geography advocates rather universal economic motives related to rational decision-making, without paying attention to space-specificity (or non-neutrality of space). Evolutionary approaches are more related to diversity, selection and real space, rather than universal behaviour, as this excludes adaptability of economic agents as well as lock-in situations. Examples of contributions to evolutionary thinking in geography can be found inter alia in Storper (1997), Boschma and Lambooy (1999), Maggioni (2002), Brenner (2004), Boschma and Frenken (2006), and Frenken (2007).

Over the past years the number of applications of evolutionary thinking in geography has extended. Examples can be found in:

- firm dynamics and entrepreneurship (Stam 2006);
- industrial dynamics (Boschma and Frenken 2006);
- network analysis (Barabasi and Albert 1999);
- spatial systems' evolution (Boschma 2004);
- urban growth (Andersson et al. 2006);

- knowledge flows (Maggioni 2002);
- spatial policy (Lambooy and Boschma 2001).

These applications reveal interesting features, although most of these applications are based on simplified metaphors or evolutionary symbols rather than hardcore Darwinistic modelling principles. As a consequence, there is still a range of research challenges in economic geography, in particular (i) the test on operational validity of evolutionary approaches in case of value transfer; (ii) the specification of the micro-behavioural basis of a multiplicity of factors; (iii) the matching between evolutionary behaviour and evolutionary modelling including feedback and lock-in behaviour; (iv) the design of long-range data bases in space-time evolutionary geography as the basis for advanced applied modelling.

## 7. Prospect

In modern space-time geography, including transportation science, we will most likely see a trend towards massive micro data sets on human mobility. This will prompt the need for smart spatial data management and for efficient statistical data manipulation where data mining and data kriging will play a central role.

An emergence of large data sets on space-time movements of individuals will also lead to a need for systematic comparative study, in which spatial meta-analysis on large data manipulations may play a central role.

And finally, there will be a need for better forecasting tools based on data-instigated theoretical frameworks. This may, in the framework of space-time geography, also lead to challenging issues on evolutionary data handling techniques.

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